

Affordable/Acceptable Supersonic Flight: Is It Near?

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AFFORDABLE, ACCEPTABLE SUPERSONIC FLIGHT: IS IT NEAR?

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ABSTRACT

The author takes a historical look at supersonic flight and humankind's first encounter with the sonic boom. A review is given from the 1950s to the present of the quest to understand the sonic boom, quantify its disturbance on humans and structures, and minimize its effect through aircraft design and operation. Finally, the author reminds readers that sonic boom is only one factor, though critical, in enabling an economically viable commercial supersonic aircraft.

1. INTRODUCTION

Since the late 1940s when Chuck Yeager first flew supersonically and humankind experienced the sonic boom, researchers have sought to understand how it is generated, how it can be predicted, and if it can be reduced. In addition to the sonic boom, high drag levels, increased weight, and noisy engines have also presented related and significant barriers to commercially operated fleets of supersonic airplanes. For more than 50 years, off and on, theoreticians, experimentalists, and more recently, computational experts have chipped away at these barriers---learning more with each concentrated effort. Today, I will review selected efforts over the years as we retrace that journey. I will then offer some thoughts on where we are today in our quest for routine supersonic flight. Of course, we cannot forget that engineering marvel---the English/French Concorde---which has been successfully flying for over 25 years---but it is the barriers mentioned above which have prevented the Concorde from expanding its fleet to hundreds crossing the globe each day.

2. ORIGINAL SONIC BOOM RESEARCH

When supersonic flight became a reality around 1950, its accompanying sonic boom was unexpected. Aerodynamicists knew about the shock waves accompanying associated with supersonic motion, but they did not expect these shock waves to reach the ground. People heard the booms and wondered about their source. As military aircraft increased their supersonic missions over populated areas, there were growing numbers of complaints and damage claims. Through the efforts of many researchers, the physical nature of the sonic boom had been explained by the mid 1950s.

In June 1961, the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA), released the "Commercial Supersonic Aircraft Report," known as the SST Bluebook. This report detailed that the development of a commercial supersonic transport was technically feasible, but that a major research and development program would be required to solve

many problems associated with such a venture. The sonic boom was one of the major problems. It became essential to know the level of sonic boom exposures that might be accepted by the public. The Air Force had data associated with complaints and claims they had received over their ten years of supersonic operation, but they could not correlate the generating aircraft and its location with the boom. Special operational programs were needed to assess community reaction to measured sonic booms. One of these first tests was in St. Louis in from November 1961 through January 1962. Subsequent flight programs were held at Edwards AFB in 1963, in Oklahoma City in 1964 and in Chicago in 1965. The citizens and buildings in St. Louis were exposed to sonic booms up to 3 lbs/ft², and predicted boom levels generally matched the measured signatures. Results of the study were inconclusive. It was found that for a particular boom, inside exposures were lower in intensity, existed for a longer period of time, and were more complex. Generally, the sonic booms experiences inside structures were less acceptable than those experienced outside--probably because of the rattling of items and the vibration of the structure. Researchers also concluded that there was no one level of overpressure below which acceptance is assured. And further, they determined that exposure must be considered in terms of frequency, intermittency, time of day or night and the particular signature.

In addition to the flight tests accomplished by the Air Force, NASA and later the FAA, there was tremendous effort put on all areas of sonic boom research in the United States and in Europe in the 1960s and the 1970s. In September 1963, NASA sponsored a Conference on SST Feasibility Studies. At its St. Louis Conference in 1965, the Acoustical Society of America summed up the State-of-the-Art of sonic boom. Survey papers were given on the nature of the sonic boom, sonic boom estimation techniques, design methods for minimization, atmospheric effects on sonic boom, the impact of airplane operation on the sonic boom, and the effect of sonic booms on people. The final survey paper at that conference began to assess the operation of a supersonic transport with sonic boom as only one design constraint---considering over-water supersonics only, supersonics in low population corridors, or range on the order of 3000 miles.

Research and technical meetings on sonic boom continued at a steady pace between 1965 and 1970. NASA held conferences in Washington, DC in 1967, 1968 and in 1970. AGARD held a conference in Paris in 1970, and reports on sonic boom were prepared for the Organization for Economic Co-Operation and Development (OECD) in Paris, and the International Civil Aviation Organization (ICAO) in Canada in 1970.

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In the Proceedings of the 1970 Acoustical Society's Second Sonic Boom Symposium, Editor, Dr. Herbert Ribner summarized the state of the art.

- The evolution of the sonic-boom signature from its pattern near the aircraft to the pressure signature (N-wave) received on the ground can now be predicted. Prediction occurred by either measuring the signature at several body lengths away from an aircraft model in a supersonic wind tunnel and extrapolating it to the ground, or by calculating the Whitham F Function from the volume and lift distribution of the aircraft and extrapolating it to the ground. The predictions are valid up to Mach numbers of about 3.
- Theory can predict the location of a superboom.
- Theory can also account for the effect on a sonic boom of variations in temperature, density or winds in a horizontally stratified atmosphere.
- Experiments had verified the focusing and defocusing effect of turbulence on an N wave.
- Studies have been conducted on how sonic booms affect structures, animals, the terrain, and people. The response of buildings depends on construction details, aging, pre-stressing, weathering, and other unknown factors. Though claims were made, domestic farm and zoo animals showed little response to sonic booms.
- Turbulence causes randomness both above and below the predicted nominal value of the N-wave. For measured values in which the rise time is less or the signature is "spikier," the annoyance is greater. For the N waves studies at that time, however, neither the rise-time nor the spikiness was controllable.
- Expanding on McLean's 1964 work for minimizing the mid-field signature overpressure with vehicle shaping, Dr. Richard Seebass and Dr. Albert George presented an algorithm for defining the minimizing equivalent area distribution, based on flight Mach number and altitude, and the airplane's length and weight.

In his comments on design at the 1970 NASA 3rd Sonic Boom Meeting, NASA's Harry Carlson stated that "It has become very clear that the problem of sonic boom minimization through airplane shaping is inseparable from the problems of optimization of aerodynamic efficiency, propulsion efficiency, and structural weight. Substantial improvement in any of these other factors would have a direct beneficial influence on sonic boom minimization."

3. CANCELLATION OF THE U.S. SST PROGRAM

Between 1958 and 1972, the United States invested nearly \$1B on sonic boom and supersonic research. Boeing Commercial Aircraft had been selected through a competition to build the U.S. SST, and the French and English were jointly building the Concorde. In 1972, because of sonic boom issues, concerns about the engine exhausts of an SST causing ozone depletion, and Boeing's difficulties with its SST design, the United States cancelled its SST Program. As a result of the growing public complaints about sonic boom, the U.S. also passed a law prohibiting commercial supersonic flight over the continental United States. Funding within the U.S. for supersonic and sonic boom research dropped significantly---to about \$130M over the next 10 years through the Supersonic Cruise Research (SCR) Program.

In 1972, the author was given the assignment to develop a computer code to solve the algorithm developed by Seebass and George---and to develop that code for a standard atmosphere rather than for the uniform atmosphere as developed. A further modification to the algorithm was to relax the requirement for a Dirac Delta function at the nose (which resulted in high bluntness and high drag). Upon the completion of that code, a NASA Langley co-worker, Bob Mack, and I designed 3 wing-body concepts for cruise at Mach 1.5 and Mach 2.7 based on the equivalent area distributions generated using the SEEB (Seebass and George based) algorithm. Three, non-cambered 6-inch concepts were designed for this first step in validating the Seebass-George methodology. The six-inch models were at that time the largest sonic boom models to be tested in the Langley 4X4 ft. Unitary Plan Supersonic Wind Tunnel. Original models tested in the tunnel during the 1960s were from 0.25 inch up to 1 inch. The size of the models was driven by the need to measure far-field signatures to ensure linear theory was valid---about 50 body lengths away. As confidence in the extrapolation methods grew, signatures could be measured closer to the body and the model size could become larger.

The Mach 1.5 and Mach 2.7 designs were tested and the measured pressure signatures were extrapolated to the ground using the Wallace Hayes computer code for a horizontally stratified atmosphere. Results for the Mach 1.5 design compared very well with the ideal signature as predicted by the SEEB code. Results for the Mach 2.7 designs were not as spectacular. Though the forward sections of the signatures matched well, the extrapolated signature had a larger growth in pressure just ahead of the expansion. Possible causes for the growth were hypothesized as possible non-linearities in the Mach 3 flow, which could not be captured by the SEEB code, or boundary layer growth on the model which was not accounted for in the theory. Generally, however, it was felt that the Seebass-George Minimization Theory had been validated. Before a follow-on set up models could be designed, the SCR Program was cancelled, and funding for sonic boom research was dropped for nearly 6 years.

4. HIGH SPEED RESEARCH PROGRAM

In 1986, NASA awarded contracts to Boeing Commercial Airplanes and Douglas Aircraft Company to assess the market and technology needs for a viable supersonic transport---this in response to two national reports which stated that the United States should have R&D programs supporting supersonic transport technology. Results of the feasibility showed that environmental concerns---sonic boom, community noise, and engine emissions--- should be the top priority for such a vehicle. The reports also stated that the economic viability of a supersonic vehicle would be tremendously reduced if restricted to only over-water routes.

To help organize the sonic boom research program for the High Speed Research Program, a workshop was held at Langley Research Center in January 1988 to assess the state-of-the-art in sonic boom and to give direction and priorities to technologies needed. Dr. Wallace Hayes of Princeton University, Dr. Albert George of Cornell University, Dr. Allan Pierce of Georgia Tech, and Dr. Clemans Powell of NASA Langley discussed weaknesses in prediction and minimization methodology when nonlinear flow is involved such as near the model or at higher Mach numbers, the lack of a single descriptor for a sonic boom, and the lack of an understanding of atmospheric effects on that descriptor and a correlation of human acceptance with that descriptor. Need for an experimental means of validating atmospheric effects without prohibitively expensive flight tests was also discussed. The general consensus of the sixty-odd researchers present at the workshop was that research should begin immediately, and that top priority should be given to: (1) establishing the metric and criteria for an acceptable waveform; (2) designing a viable aircraft to an existing shaped waveform; and (3) quantifying the atmospheric effects on "shaped waveforms."

Though the High-Speed Civil Transport (HSCT) feasibility studies originally considered Mach numbers from 2 to 25, initial studies showed that productivity gains dropped significantly beyond Mach 4. By 1989, the upper limit of consideration for the HSCT Mach number had become 3. Because Mach numbers above 3 were no longer in consideration, there was no emphasis placed on sonic-boom predictions at the higher Mach numbers. In 1992, there was an HSR programmatic decision to establish 2.4 as the design Mach number. Other design parameters included 300 passengers and a range of 6,000 n.mi.

The organization of the sonic boom research within HSR followed the general outline recommended in the 1988 Workshop: Configuration Design and Operation, Acceptability Studies and Atmospheric Propagation Effects. Within the configuration design element of the program, there were design studies, wind tunnel tests, CFD analysis, flight tests and performance studies. Within the acceptability area of the program, there were sonic-boom simulator studies, in-home studies, community surveys and structural response studies. Finally, within the atmospheric propagation effects of the program, research included absorption studies, turbulence

effects, propagation model development, caustics and secondary booms.

Progress in Design Studies

The first low-boom designs developed in the HSR Program endeavored to include more characteristics of real airplanes than the flat wing-body design of the mid 1970s. In 1990, Mach 2 and Mach 3 twisted wing-body-nacelle concepts were designed using the Whitham F Function based minimization method---the Mach 2 to product a flat-top signature, and the Mach 3 at minimum shock or "ramp" type signature. During the tests of these model, large, unpredicted shocks emanating from the flow-through nacelles were encountered. For tests of the models without the nacelles, again the minimization theory was validated---generally at both Mach numbers, but more precisely for Mach 2.0.

The next generation of low-sonic boom designs, begun in 1991, had two new objectives: to correct the nacelle integration concerns and to improve the overall aerodynamic performance of the low-boom concept. Several industrial and government partners participated in this design cycle--both for the sonic boom analysis and the performance analysis. Modifications were made to the F-function analysis method to ensure that inlet shocks were predicted. Also, for the first time in sonic-boom analysis was accomplished with powerful, nonlinear CFD methods. Because the traditionally-used Whitham Theory is only valid at mid- to far-field distances, CFD methods are the only means of generating a near-field signature---one which can be compared directly with wind-tunnel data, and one in which signature features can be directly correlated with configuration features. For several of the models in this cycle, CFD methods were used to iteratively design the desired signature. The use of CFD had also become more imperative as wind-tunnel models became larger in order to incorporate the increasingly realistic features such as twist and camber, and nacelles. Larger models necessitated measuring the signatures at closer and closer distances. All sonic boom models built during the HSR Program were 12 inches in length and measurements were taken at 2 to 3 body-lengths away. Test results on this generation of models met with moderate success. Shocks from the nacelles were successfully embedded within the expansion wave of the vehicle, and while the predicted ground signature was not an N-wave, the slope of the pressure growth was much steeper than predicted. Because the initial signatures were now being measured quite close to the model, concerns for 3-D effects or uniform atmosphere effects began to arise.

Because of the varying levels of systems analysis which accompanied the low-boom designs begun in 1991, and because the impact of sonic-boom reduction techniques on the mission performance is a critical measure of success, an attempt was made to conduct a consistent analysis of the mission performance on all of the designs.

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